THE SOLAR ATMOSPHERE AND THE STRUCTURE OF ACTIVE REGIONS

under the direction of

P.A. Sturrock

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1. Coronal Holes
(W.M. Adams and P.A. Sturrock)

The work of Burton (1968), Tousey et al. (1968), and Munro and Withbroe (1972) has established the existence of "holes" in the corona characterized by abnormally low densities and temperatures; and Krieger et al. (1973) have found that such coronal holes appear to be the source of high-velocity, enhanced-density streams in the solar wind as observed at the earth's orbit. It has further been noted by Altschuler et al. (1972) that coronal holes appear to be associated with regions of diverging magnetic field in the corona. We set out to test the hypothesis that coronal holes may be caused by an increased flow of energy into the solar wind resulting directly from this diverging magnetic field pattern.

In order to accomplish our objective it was first necessary to develop models for the principal energy flows in the transition region and corona. As far as the energy input into the corona is concerned, we made no detailed assumptions about its nature beyond taking it to be a constant, independent of conditions in the transition region and corona. The energy output from the corona was assumed to be dominated by two energy sinks: heat conduction downward into the transition region, and the flow of energy outward into the solar wind. For the first of these we developed a simple model for the downward heat flux as a function solely of the temperature at the base of the corona: this was accomplished by making the plausible assumption that the temperature structure in the region of interest is dominated by the requirement that the heat flux be constant. For the solar wind we used a simple polytrope model with a single polytropic index holding

all the way out to infinity: this gave us an outward energy flow that depended not only on the temperature at the base of the corona but also on the rate of divergence of the field lines.

Having once developed mathematical expressions for our two coronal energy outflows, we simply set their sum equal to a constant (determined by the values they take on for the quiet sun); and we were then able to solve numerically for the temperature and density at the base of the corona as a function of the rate of divergence of the field lines. The results were then compared with the observed parameters for the coronal hole studied by Munro and Withbroe (1972). The agreement between the two was remarkably good considering the approximate nature of the models used in our calculations, and it seems to lend considerable support to our original hypothesis (i.e., that diverging field patterns actually cause coronal holes). This work is essentially complete and is about to be submitted for publication.

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2. Loop Prominence Systems
(S.K. Antiochos and P.A. Sturrock)

In our previous report (Antiochos and Sturrock, 1973) we described a one-dimensional model of a loop prominence. We have compiled a preliminary computer code for this model using a Lax-Wendroff differencing scheme.

The equations used are in Lagrangian form with x as the independent variable, where

$$x \equiv \int_0^s n(s')\, ds' , \qquad (1)$$

and $s = 0$ corresponds to the top of the loop, so that x measures the total amount of plasma contained in a length s of the loop. At present, we are computing the dependent variables, e.g. temperature, at 32 uniformly distributed values of x. Thus we are simulating the loop by 32 slabs of plasma, all containing equal mass. The physical width of these slabs, Δs, is not a constant; however, since we take a size scale of 10 - 50,000 km for the loop, we obtain a spacing of $\sim 10^3$ km. This spacing is smaller than the scale height of the plasma, but not much smaller than the size scale of observed condensations ($\gtrsim$ 5,000 km). Therefore, for production runs, we intend to double the number of slabs and obtain a spacing of $\sim$ 500 km.

In our code, the space increment Δx must be held constant for proper centering of the difference equations, but the time increment Δt is allowed to vary. It is chosen to satisfy the stability criterion for the difference scheme:

$$\Delta t \le \frac{1}{10} \operatorname*{Min}_{i} \left(\frac{\Delta s_i}{|v|_i + c_i} \; , \; \frac{p_i (\Delta s_i)^2}{\kappa_i T_i} \right) , \tag{2}$$

where v is velocity, c is the speed of sound, p is pressure and κ is thermal conductivity; i runs over all slabs. The factor of 1/10 is included as a margin of safety because the criterion above is known to be completely valid only for the linear equations.

We are presently incorporating into our code a method that will enable us to check on the accuracy of our solution. The method is the following; our equations are of the form:

$$\frac{\partial f}{\partial t} = G \tag{3}$$

where G is a function of the dependent variables and their spatial derivatives. The Lax-Wendroff difference equations allow us to compute $f(t + \Delta t)$ from $f(t)$ to second order accuracy in Δt. Equation (3) now gives us $\left.\frac{\partial f}{\partial t}\right|_{t + \Delta t}$ to the same accuracy. We can check this estimate for f, $f_1(t + \Delta t)$, by substituting $G_1(t + \Delta t)$ into the Crank-Nicholson difference equation, (Richtmeyer and Morton, 1967):

$$f(t + \Delta t) = f(t) + \frac{\Delta t}{2} \left[f'(t) + f'(t + \Delta t) \right] . \tag{4}$$

The right hand side of (4) gives us a new value for f at $t + \Delta t$, $f_c(t + \Delta t)$. By comparing f_1 and f_c, we can monitor the accuracy of our solutions. Another advantage to computing f_c is that the Crank-Nicholson difference scheme is always stable. Thus by using f_c instead of f_1, we should be able to relax our stability criteria. At the moment, our code takes ~ 2 minutes of computer time on the 360/67 to

follow the plasma for $\sim$ 10 minutes of real time.

In our preliminary results we find that for a loop size of 50,000 km, initial density 10^{11} cm^{-3}, and initial temperature 10^{7} °K, it takes $\sim 10^{3}$ seconds for all the slabs to cool below 10^{6} °K. This agrees with what we would expect for plasma cooling mainly by conduction. For the above parameters,

$$\tau_{cool} \approx \frac{2nkT}{(\kappa T/H^2)} \approx 10^{3.3} \text{ s} \quad . \tag{5}$$

However, these computations involved the assumption of zero velocity at the base of our model. This assumption should have little effect on the cooling rate for the plasma at the top of the loop, but it does exclude the possibility of calculating the amount of plasma evaporated from the chromosphere due to the downward heat flux. We are therefore modifying our code so that we can include several slabs of cold chromosphere plasma. With this code we hope to be able to simulate more accurately the behavior of plasma in a loop prominence.

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3. Force Free Magnetic Fields and Their Role in Solar Activity (C.W. Barnes and P.A. Sturrock)

During the last contract period, we have resumed our work on force-free fields last studied by us several years ago (Barnes and Sturrock, 1972). We are studying the mechanism by which mechanical energy of motion in the photosphere is transferred to stored field energy and thence to kinetic energy in the ejected plasma from the resulting flare or prominence. We demonstrated in our previous work that the energy stored in twisted force-free fields can greatly exceed the stored energy in an equivalent configuration with completely open lines. The means by which the stored energy is released (suddenly or gradually) and the rate at which field lines are open is as yet unknown, however. The complete solution to this problem will ultimately involve the solution of the time dependent fluid equations coupled with Maxwell's equations, probably in two or three dimensions.

We have concentrated on the study of static force-free magnetic-field configurations based on a spherical boundary surface, the configuration being of azimuthal symmetry. This is clearly a step in the right direction for the study of solar magnetic fields. Furthermore, limiting cases of this configuration can be compared with both types of geometry which have previously been analyzed at Stanford. For instance, in studying a ring-like sheared dipole near the equator, we approach the configuration analyzed by Sturrock and Woodbury (1967). In going towards a small circular sheared ring dipole at one of the poles, we approach the configuration analyzed by Barnes and Sturrock (1972). It has proved to be convenient to replace the radial co-

ordinate by ℓ, the logarithm of the radius. The equations governing α and γ, which characterize the field, then do not depend upon the radius explicitly, which is a computational simplification. It is also an advantage that the computational mesh is most finely divided near the surface where the field changes most rapidly, making best use of computer time. In these coordinates, furthermore, the aspect ratio of the cells defined by the mesh is constant in radius, so it is convenient to work with mesh spacing which is uniform in ℓ as well as in the latitude θ. The usual central-difference approximation has been made for the differential operations, yielding two coupled difference equations linear in α and γ at the center mesh point of each finite-difference stencil. Thus α and γ can be found explicitly at these points. A relaxation procedure is used to solve the equations with a variable relaxation parameter which self-adjusts during the course of the computer run to maximize convergence.

The code was written to use a mesh as fine as 100 points on a side. However, at the early stage of the runs, we used as coarse a mesh as possible to cut down computation time. We have regarded this particular model primarily as a test project for assessing various procedures for speeding up the convergence of the computation. Finding the most efficient use of computation time is an essential step toward our later goal of computing complex three-dimensional field configurations.

We have recently performed a series of runs to determine the variation of stored energy with shear angle for a ring dipole at approximately 45° latitude. By choosing several surface field distributions (essentially varying the dipole width), we are also studying

the dependence of the stored energy on both the shear angle and the dipole width.

We have also begun the investigation of an effect which is important for our understanding of erupting prominences and of flares. As a small practical step towards our understanding of the complex process of eruptive instabilities (Barnes and Sturrock, 1972), we wish to study the variation of the total stored energy as field lines change from a closed configuration to an open configuration. We suspect that there is a potential barrier to this process, but that the barrier may be quite weak. We are therefore investigating the effect on the magnetic field pattern of "mechanically" displacing the field lines along an (approximately) radial line to simulate the opening up of the field lines in response to the ejection of a mass of plasma.

We have also begun to study the possibility of performing a full three-dimensional treatment of the magnetic field problem, which would allow us to treat irregular field patterns as well as configurations which are inherently three-dimensional such as a twisted loop. We believe that the key to this, with computers and budgets at our disposal, is our ability to use a fairly coarse mesh. We feel that mesh sizes of the order 30 x 30 x 30 are economically practical, and we are attempting to determine whether they can adequately model the physics of the problem. As a first step, we are running two-dimensional codes with coarse meshes as well as fine meshes and we hope in this way to be able to predict our chances of success for the three-dimensional calculation.

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4. Aircraft Accident Analysis
(J.W. Knight and P.A. Sturrock)

We are continuing to examine the possibility that a correlation exists between aircraft accidents and solar activity. First we searched for a correlation between aircraft accidents and the G_p index of geomagnetic activity using the method of superposed epochs (Chree and Stagg, 1927). This did not produce promising results so we decided to explore other methods of analysis. As we indicated in our last proposal (Proposal No. IPR 19-74), the examination of least-square spectral estimates produced provocative if not convincing evidence for an association between the G_p index and aircraft accidents.

To further assess the significance of peaks appearing in these spectra, we generated least-square spectra near periods of 6.75 and 13.5 days for each year of the available data. The results did not support the proposition that geomagnetic activity is the intermediary for an influence of solar activity on aircraft accidents, since the aircraft accident spectra show the strongest peaks in 1967, while G_p spectra have no discernable peaks in 1967.

We were thus led to examine other possible intermediary phenomena. Wilcox et al. (1973) found a correlation between the average area of low pressure troughs observed during winter in the Northern Hemisphere at the 300 mb level (9000 m) and the interplanetary magnetic field structure (sector structure). We obtained a least-square spectrum of the vorticity index used by Wilcox et al. (1973) in their analysis. The spectrum shows a strong peak at 13.5 days (better than .1% by the

F test); however, there are no significant peaks at 6.75 or 27.2 days as in the G_p and aircraft accident spectra. We do not feel that a connection between solar activity and aircraft accidents can be inferred on the basis of the vorticity spectrum. It should be noted that the correlation found by Wilcox et al. (1973) existed only for the winter months when the average number of accidents per day is low. The tests for correlation using least-square spectra were therefore inconclusive so a more direct method of searching for a correlation seemed appropriate.

The maximum likelihood technique of statistical analysis has properties favorable for the analysis of large samples (Rao, 1965). We have used a simple model which is amenable to analysis. In particular, we have taken the integrated probability density of aircraft accidents for day i of the sample period to be

$$P_i = \nu e^{\alpha y_{i+k}} , \tag{1}$$

where y_i can be the time series of any proposed intermediary between solar activity and aircraft accidents. The lag k and the depth of modulation α are to be varied to maximize the likelihood. The likelihood for a set of aircraft accident data, N_i is

$$L = \prod_{i=1}^{n} \frac{e^{-P_i} P_i^{N_i}}{N_i!} . \tag{2}$$

We wish to maximize the "relative likelihood", that is the ratio of the maximum likelihood to the likelihood for the case $\alpha = 0$. We will also assume that the average value of y_i is 0 and that its variance is 1. All sets of y_i will thus need to be normalized before calculations are performed, but the analysis is much simplified. The value of α

which maximizes the natural logarithm of the relative likelihood ($\mathcal{L}$) for a given lag can be easily shown to be

$$\alpha = \frac{\sum_{i=1}^{n} N_i \, y_{i+k}}{\sum_{i=1}^{n} N_i} \quad , \tag{3}$$

and the value of $\mathcal{L}$ for this α is

$$\mathcal{L} \equiv \ln L_{rel} = \frac{1}{2} \frac{\left(\sum_{i=1}^{n} N_i \, y_{i+k} \right)^2}{\sum_{i=1}^{n} N_i} \quad . \tag{4}$$

The maximum likelihood technique has the advantage that, in the limit of large sample sizes, the estimates of the parameters (in this case α and k) are normally distributed with variances given by the diagonal elements of the inverse information matrix. In the present case the information matrix is diagonal and the variance estimate V_α for the parameter α is

$$V_\alpha = \frac{1}{\sum_{i=1}^{n} N_i} \quad . \tag{5}$$

The variance V_k for the parameter k is

$$V_k = (\partial^2 \mathcal{L} / \partial k^2)^{-1} \tag{6}$$

where the derivative is evaluated at the point where $\frac{\partial \mathcal{L}}{\partial k} = 0$ and $\frac{\partial \mathcal{L}}{\partial \alpha} = 0$. Since calculations can be conveniently performed only for

integer values of k, the position of the peak and the variance estimates were obtained by approximating $\mathcal{L}(k)$ by a polynomial near the peaks.

The G_p index is quite noisy, the variance being 15 times the average. Therefore, the G_p index was smoothed with a Gaussian window of 1/e half-width 5 days. Then the raw G_p index smoothed with a gaussian window with a 1/e half-width of 20 days was subtracted from the smoothed G_p index to remove long term trends. (It should be noted that the widths of the smoothing windows could also be considered parameters which could be varied to maximize the likelihood. We have not attempted this as yet.) We have calculated $\mathcal{L}$ and α as a function of k, for k in the range -150 to 150 days. There are 5 peaks for which α is different from 0 by more than three estimated standard deviations (3σ). The largest of these occurs at $k = -10.86 \pm 1.58$ days (quoted error is 3σ) corresponding to some dependence of the probability of an aircraft accident on the smoothed G_p index ~ 11 days before. There is some evidence of terrestrial effects of solar activity with delays of this approximate length. The work of MacDonald and Roberts (1960) indicated that solar activity may affect the development of low pressure troughs. The maximum development of the affected troughs occurred 7-12 days after selected active days. Again it should be noted that the effect was evident only in the winter months. Although these facts are suggestive, when individual years were examined, the only year in which a peak occurred above the 3σ threshold was 1967 ($k = 11.99 \pm 1.14$). Peaks near this delay occurred in other years, but not at the 3σ level. It may be significant that the delay indicated is of the same order as that for low

pressure trough development and that the maximum likelihood technique and the least-square spectrum both show the largest effect in the same year. However, 1967 also has the largest average number of accidents per day of the years considered. The average number of accidents per day is ~ 22% higher than would be interpolated from the other six years. This may be a real effect or an artifact of the reporting procedure. We have asked the National Transportation Safety Board for possible explanations of the anomaly.

We are not able to make any firm statements about the possible existence of a correlation between aircraft accidents and solar activity on the basis of the analysis we have performed to date. Further investigation would be necessary before concrete conclusions could be drawn.

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5. Correlation of Heart Attack Mortality and Solar Activity
(B.J. Lipa and P.A. Sturrock

In recent years many observations in the USSR (Gnevyshev and Novikova, 1971, 1972) have suggested the existence of a direct effect of solar activity on the earth's biosphere, including man. In view of these observations, it has been suggested in the USSR that a new branch of science, to be known as heliobiology, be introduced. Evidence for the effect of solar activity includes a comparison between the daily cardiovascular mortality in Sverdlovsk during the period 1960-1966 and the local c-index of geomagnetic activity, and a superposed epoch study over a period of 8 years giving the relationship between myocardial infarction mortality in Sverdlovsk and days from the start of a magnetic storm. All results quoted show a strong positive correlation between mortality and geomagnetic disturbance; for example the mortality rate on days with a c-index of 2 is 3.43 times that on days with a c-index of 0. Unfortunately, the statistical significance of these results is unknown.

With the aim of checking the validity of these results and performing a proper statistical analysis, daily heart attack deaths over 1964-1965 for 31 U.S. cities were obtained from the National Institute of Health. The death rates for the 31 areas were combined, and periodicities of non-physical origin were removed. These included variations with the day of the week, seasonal variations, and long term secular trends. The resulting daily figure was compared with C_p indices derived from data issued by the National Oceanic and Atompsheric Administration (NOAA).

Three types of analysis were performed:

1) The mean death rate was calculated for G_p values in the ranges 0 - 10, 10 - 20 etc. These values and the associated error of the mean were plotted for lags and leads of up to 7 days. In no case was there any statistically significant trend in the death rates with increasing geomagnetic disturbance. Results for zero lag are shown in Figure 1.

2) A superposed epoch analysis was performed. Days were selected which had a value of the G_p index which was greater than the mean by x times the standard deviation, where x = 1, 2, . . . 5. Data in the range up to 15 days from the selected days were superposed and the death rates averaged. Results for x = 2 are shown in Figure 2. The standard error of the mean is the same for all points plotted and is shown to the right of the diagram. For all values of x, there was no statistically significant departure from the mean death rate as a magnetic storm approaches or recedes.

3) The correlation coefficient and its standard deviation were calculated for lags and leads of up to 14 days. In all cases, the correlation coefficient differed from zero by less than two standard deviations. It is concluded that the correlation is not significantly different from zero.

Gnevyshev and Novikova (1972) found a strong correlation between death rates in a particular city and local magnetic indices. To check this work, local K-indices from the Fredericksberg, Honolulu and Tucson observatories were obtained from NOAA and compared with the heart attack death rates in Washington D.C., Honolulu and Phoenix,

respectively, using the 3 point analysis described above. In no case was a statistically significant correlation observed.

These negative results strongly disagree with those of Gnevyshev and Novikova. Possible reasons for this disagreement are as follows:

1) USSR cities analyzed were generally at high latitudes, where magnetic activity is greater. As a partial check on this effect, the correlation coefficients between heart attack deaths in Minneapolis and Portland and global G_p-indices were calculated. They were not found to differ significantly from zero.

2) Gnevyshev and Novikova had data covering longer time spans.

3) Causes of heart attacks in the US may differ from those in the USSR. In addition the magnetic field environment of the average person may be different.

On the basis of our analysis, it is not felt that solar activity has a direct effect on heart attack mortalities in the US, either on a local or on a nation-wide basis. A brief report on this negative result will shortly be submitted for publication.

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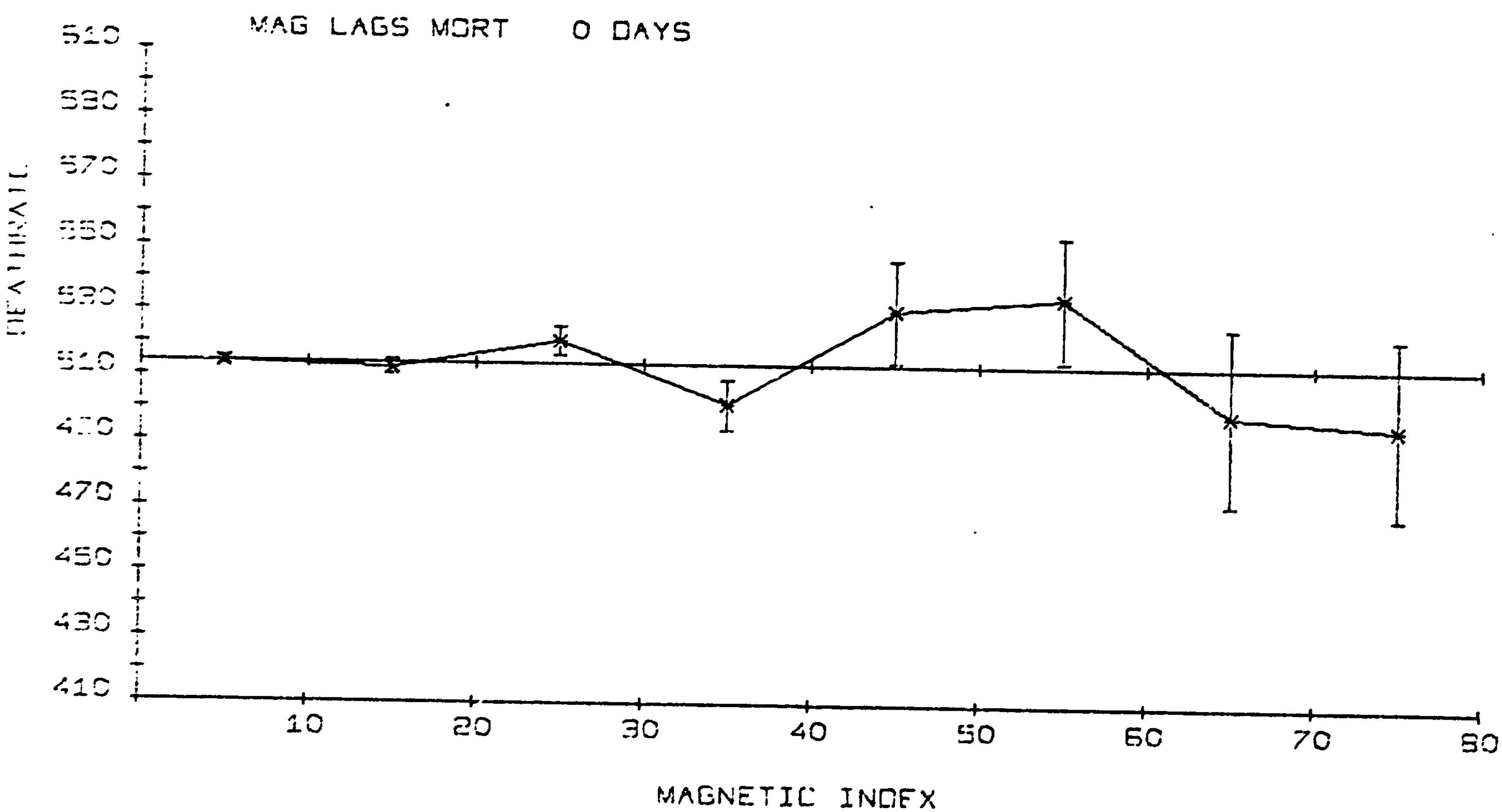

Figure 1. Death rates for 31 US cities plotted against G_p index.

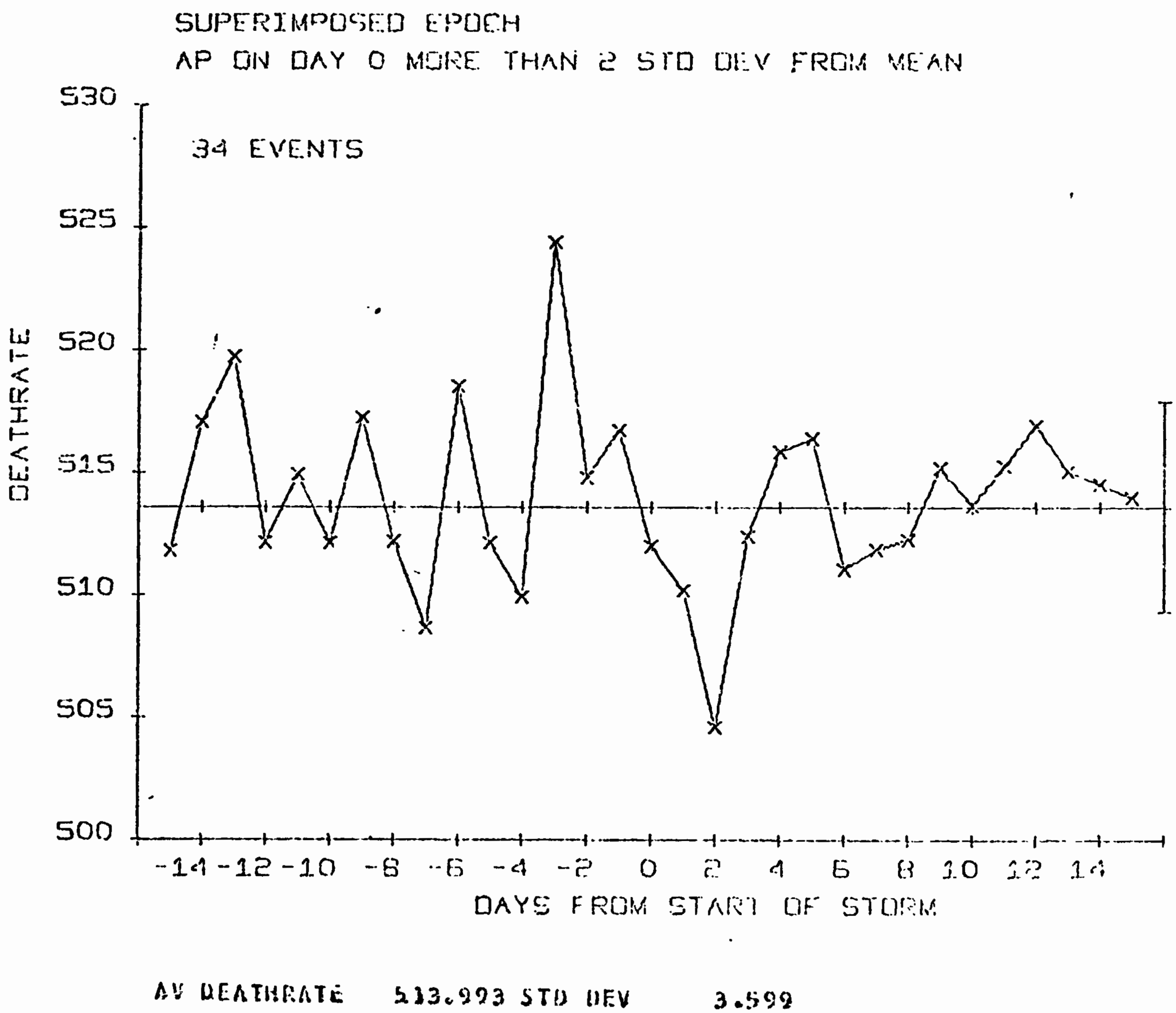

Figure 2. Superimposed epoch analysis. Death rates are for 31 US cities.

6. Hard X-Ray Emission in the Plasma Focus (C. Newman and V. Petrosian)

In our last status report, we discussed an application of our work on solar x-ray bursts to a phenomenon observed in the laboratory, namely, the production of hard x-rays in the plasma focus device. We reported that a model involving large induced axial electric fields could explain the anisotropy of the observed x-ray spectrum no matter whether the x-rays are produced in the focused plasma itself or in the walls of the device. The total energy in the x-rays above 100 keV could also be explained, but different numbers of accelerated electrons were required in the two cases. The applicability of our solar work to this phenomenon, as well as the similarity of the hard x-ray energy spectrum in the plasma focus to flare-related x-ray energy spectra, indicates that similar x-ray production mechanisms may be operative in the two cases and points up the possibility of studying solar processes in the laboratory, as has already been pointed out in the literature (Elton and Lie, 1972). This work has now been written up in report form (Newman and Petrosian, 1974).

We have now modified our model in order to explain new experimental evidence as to the source of the hard x-rays and to account for the lifetime of the x-ray pulse. First, we have had to discard the idea that the walls are the source of the x-rays since Lee (1974), using pinhole cameras to observe the source, observed no x-rays coming from the walls while at the same time observing hard x-rays from the plasma; thus, for our model to be valid, we require that about 10^{18} electrons be accelerated to 100 keV or more and that they be slowed down by some

mechanism (probably an electric field resulting from the charge imbalance, which occurs when these electrons try to leave the focus region) before they reach the walls.

Second, our model, as originally conceived, would have predicted a very short ($\sim$ 5 n sec) hard x-ray pulse, in conflict with the observed 40 - 50 n sec lifetime. We have overcome this difficulty by pointing out that although the accelerating electric field is strong only when the collapse of the current sheet is in its final stages (Newman and Petrosian, 1974), this collapse does not occur simultaneously at all points on the axis. (See Figure 1 of Newman and Petrosian, 1974, or Figure 16 of Status Report No. 4.) The end of collapse, or the beginning of the focus phase, occurs first near the anode and at progressively later times for points at increasing distance from the anode; the focused plasma, which may be interpreted as the region of final collapse, is observed (Jalufka and Lee, 1970) to move with an axial velocity of 3 - 4 x 10^7 cm/sec. Thus, while the strong axial electric field is present at a given point on the axis only for a short time, the focused plasma moves in such a way that it sees this field for a much longer time. In this manner hard x-rays can be produced for periods up to 50 n sec.

Our revised model is being written up and will shortly be submitted for publication.

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7. X-Ray Emission from Solar Flares
(V. Petrosian)

The observed time variation, polarization and spectrum of the impulsive solar x-ray bursts (IXB's) have led us to the model whereby the x-rays (and perhaps optical and ultraviolet radiation) emitted during solar flares are produced by a beam of high energy electrons directed toward the photosphere from somewhere in the corona. In this model the impulsive hard (> 10 keV) x-ray bursts are produced by bremsstrahlung of the beam with chromospheric ions. Most of the energy of the beam, however, is lost through long range coulomb collisions, plasma oscillations and ionization and appears as thermal (soft) x-rays, H α, white light, etc.

The details of this model have been published (Petrosian, 1973), where it was shown that the observed polarization (Tindo et al., 1970) and steepening of the spectrum beyond 100 keV (Frost, 1969) of IXB's is a natural consequence of the model (cf. also Haug, 1972, and Brown, 1972). Since the angle between the electron beam and the line of sight changes with position of the burst on the solar disk, the model also predicts systematic variation of IXB characteristics with solar longitude. For a given total energy $\mathcal{E}_e$, low energy cutoff E_1 and spectral index δ of the electron beam our previous calculation shows that the strength of IXB's should increase by a factor of about 2 from the center to the limb. This variation is much smaller than the range of the observed strengths of IXB's (more than two orders of magnitude), most of which may be ascribed to the dispersions in the intrinsic parameters $\mathcal{E}_e$, E_1 and δ. It therefore becomes difficult to separate

the variation due to the longitude from the variation due to the intrinsic parameters. One must have a large sample of bursts and take into account the observational selection effects in order to determine the longitude variations.

There are now few such samples available, the latest of which (from OSO-7) have been analyzed by Datlowe, Elcan and Hudson (1974). Incorporating the observational selection effects associated with this data, we find that the model predicts correctly the observed softening of the spectra of IXB's from center to limb. We also find that, contrary to one's initial expectation, once the observational selections are properly taken into account, the frequency of occurrence of IXB's should be nearly independent of solar longitude. This is in quantitative agreement with observations (Roy and Vorpahl, 1974). Finally, the model also predicts that, for a sample of bursts, the average burst strength and the ratio of soft-to-hard x-ray fluxes should both be independent of burst position on the solar disk. Apparently these assertions also agree with observations (McKenzie, 1974).

A pape describing the above results has been submitted to The Astrophysical Journal. In this analysis, there are certain assumptions made about the dispersion in the parameters $\mathcal{E}_e$, E_1 and δ of the bursts. The data available at the present time does not allow us to determine the distribution of these parameters fully. However, we are encouraged with the quantitative agreement between the prediction of the model and observation. We hope that, as more data becomes available, we can begin to obtain more information about the distribution of the relevant physical parameters characterizing the solar flare. This in

turn will give information about the energy source of the flares and the physical conditions in them.

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